MAPPING WILDFIRE FUELS USING IMAGING SPECTROMETRY ALONG THE WILDLAND URBAN INTERFACE

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ABSTRACT

Landscape-level fuels information is an essential component for developing a fire management strategy in Southern California. We present an overview of methodologies for mapping fuel properties using hyperspectral remote sensing data coupled with collateral information from a geographic information system (GIS). An interagency coalition, including the National Park Service, USDA Forest Service, Los Angeles County Fire Department and University of California at Santa Barbara and Davis, has been working since 1994 to develop wildland fuel mapping techniques for coastal Southern California. Initial research focused on the Santa Monica Mountains (SMM), where fall/spring seasonal pairs of Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) data have been acquired and analyzed from 1994 to present. More recent analysis has expanded to include the Santa Barbara Front Range starting in spring, 1998. Techniques have been developed for measuring green live biomass, ratios of live to dead canopy components, live fuel moisture, and vegetation species. To improve the accuracy of AVIRIS derived species maps, we have recently acquired 4 m resolution AVIRIS data over portions of the SMM in Fall, 1998. To test our products, these fuels layers are being integrated into fire spread simulations of the 1996 Calabasas and 1998 Ogilvy fires. These fires are considered ideal tests because they are well characterized and because AVIRIS data are available prior to each fire. Initial modeling efforts attest to the difficulty of translating remotely sensed attributes to fuel properties used in fire spread simulations. Our initial focus has been on incorporating live green biomass, live fuel moisture and landcover class into the models. In order to scale up our efforts, we are also investigating the use of SeaWiFS, an eight channel sensor with 1 km resolution as a means of assessing daily changes in vegetation properties over large regions. The timing of this study is critical for the development of techniques for calculating biomass accumulation and live fuel moisture prior to the arrival of satellite-based imaging spectrometers similar to AVIRIS in late 1999.

Keywords: AVIRIS, chaparral, wildfire fuel mapping, fuel moisture, classification

INTRODUCTION

Chaparral communities represent one of the most fire-adapted ecosystems in California, reaching their maximum extent in Southern California and covering 3.5M ha or 5% of the land area of the state (Weislander and Gleason, 1954). In chaparral, topography, water availability, vegetation type and stand age play critical roles in controlling biomass accumulation and seasonal variability in vegetation moisture. These factors vary widely over small spatial scales, making direct field measurements of species, moisture and biomass difficult or impossible and necessitating the use of remote sensing (Roberts et al., 1998a) and/or predictive models in a GIS to map wildfire fuels (e.g. Burgan and Shasby, 1984; Yool et al., 1985). Due to extensive urbanization of chaparral shrublands, the interactions between urban encroachment, climate, vegetation, topography, and fire hazard have become a critical concern in many areas. For example, a series of fires in the autumn of 1993 burned 22,000 ha from Simi Valley in the northeast to the coastal city of Santa Monica within a few hours (Green Meadows fire). The Painted

Cave fire of Santa Barbara burned 2,000 ha over a period of only 12 hours on June 27, 1990, destroying 640 structures at a cost $250 million dollars. Potentially, the most destructive fire in California history occurred along the wildland/urban interface in Oakland, California in 1991. This fire, which only burned 650 ha, destroyed 2,700 homes, businesses and apartments, cost 1.7 billion dollars and had 25 fatalities (Gomes et al., 1993).

Chaparral species are well adapted to frequent fires and the volatile organic compounds in some species actively promote ignition and fire spread (Philpot, 1977). As a fire-adapted natural ecosystem, chaparral represents a major source of fire hazard in the region. Rapid urban growth along the wildland interface combined with high fuel loads and a potential increase in the frequency of large fires suggest that the problem will worsen significantly within the coming decades. Fire management is further complicated by extreme weather events such as Santa Ana Winds and Sundowners, which typically occur in late summer and fall and result in strong winds and hot and dry conditions that promote uncontrollable wildfire. In the Santa Barbara area five of the six major fires between 1950 and 1991 occurred during Sundowners (Ryan, 1996). In the SMM and Los Padres National Forest, recent research by Keeley et al., (1999) and Moritz (1997) suggests that most large fires occur under such extreme weather conditions and that recent fire management strategies, while reducing the size of small fires, have had little impact on fire frequency and extent under extreme conditions. Nevertheless, there is a clear need for up to date, accurate information on fuels along the wildland/urban interface where fire management strategies may significantly reduce the loss of life and structures.

Remote sensing is widely recognized as a critical tool for large area fuel mapping (Burgan and Shasby, 1984; Chuvieko and Salas, 1996; Burgan et al., 1996). Traditionally, remote sensing is used primarily to classify vegetation into broad land-cover categories that are cross-walked to standard fuel models such as Anderson (1982) or the National Fire Danger Rating System (NFDRS) fuel models (Deeming et al. 1978). Direct assessment of fuels has been largely restricted to applications of the Normalized Difference Vegetation Index (NDVI) to map fuel moisture (Burgan et al. 1996). In this paper, we discuss the potential of hyperspectral remote sensing, using AVIRIS, to map wildfire fuel properties. We discuss techniques for measuring green live biomass, ratios of live to non-living canopy components, live fuel moisture, and vegetation species. We draw upon examples from research in the SMM. We summarize with a discussion of limitations we have encountered in incorporating our research results into fire spread simulations and an overview of a research strategy that incorporates hyperspectral remote sensing into a broader strategy for mapping fuels over large geographic areas.

BACKGROUND

Traditional Remote Sensing for Hazard

Most research has focused on fire hazard assessment using broadband remote sensing. The most common approach is to classify vegetation into fuel classes then combine this information through a GIS with collateral information such as slope, aspect, elevation and fire history to assess hazard or fire spread (Cosentino et al., 1981; Burgan and Shasby, 1984; Yool et al., 1985; Chuvieco and Congalton, 1989; Chuvieko and Salas, 1996). Chuvieko and Congalton (1989) and Chuvieco and Salas (1996) used Landsat TM data to classify vegetation by fuel class then used elevation, slope, aspect and proximity to roads to generate a fire hazards index. Burgan and Shasby (1984) merged Landsat MSS, aerial photography and digital elevation data to map seven fuel classes near Missoula Montana to quantify hazard based on the energy release component of the NFDRS fuel models. Changes in fuel moisture were modeled from digital elevation and weather data to predict dynamic changes in fuel moisture. Cohen (1991) measured reflectance of several chaparral dominants to monitor spectral changes in foliage through a growth season. He evaluated the tasseled cap as a means of monitoring seasonal drying in vegetation as changes in greenness, brightness and wetness. Stow et al., (1993) extended the use of the tasseled cap to analyze a pair of TM scenes during the 1986-1987 growing season in Southern California. The region was stratified by vegetation community type, stand age (fire history), slope and aspect. They found that late season changes in greenness for mixed chaparral varied with stand age and matched field measures of total and live standing biomass, although seasonal changes in illumination dominated. Burgan et al., (1996) describe the use of AVHRR derived NDVI as a means of monitoring temporal changes in vegetation moisture. They discuss three measures of vegetation state including visual greenness (NDVI of a pixel compared to a very green area such as alfalfa), relative greenness (NDVI relative to a seasonal maximum for a particular pixel), and an index showing NDVI departures from a running average. A recent comparison of NDVI to fuel moisture, however, suggests that a strong relationship between NDVI and fuel moisture is limited to grasslands, with a poorer relationship for shrubs and no relationship for forests (Hardy and Burgan, 1999).

Hyperspectral Remote Sensing

Hyperspectral remote sensing systems sample the electromagnetic spectrum in a large number of contiguous wavelengths. Examples of hyperspectral systems include AVIRIS, the Airborne Imaging Spectrometer (AIS), Probe-1, the Compact Airborne Spectrographic Imager (CASI), the TRW Imaging Spectrometer (TRWIS) and HYDICE. Hyperspectral remote sensing is currently limited to airborne systems. However, a series of spaceborne systems are under development including Hyperion, Warfighter, and the Naval EarthMap Observer (NEMO). These systems are scheduled to launch over the next few years with the earliest launch date set for Hyperion late in 1999. In this paper, we will restrict our discussion to AVIRIS.

Hyperspectral remote sensing has the potential of making a significant contribution towards improving the quality of wildfire fuel maps. Potential applications include 1) Accurate retrieval of apparent surface reflectance; 2) Change identification using reference endmembers (spectra of known materials) and Spectral Mixture Analysis (SMA); 3) Liquid water retrievals associated with canopy moisture and green live biomass; 4) Characterization of live and dead fuel ratios using SMA and 5) species level mapping.

At their most fundamental level, hyperspectral systems sample atmospherically transmitted, reflected radiation at a sufficient spectral resolution to characterize the chemical and physical properties of the atmosphere and surface. Provided that the sensor is well-radiometrically calibrated, it becomes possible to couple measured radiance to an atmospheric model to retrieve surface reflectance (Green et al., 1993). An example of reflectance retrieval is shown in Figure 1. In this figure, radiance for two targets is plotted in the upper frame and retrieved surface reflectance for these same targets is shown in the lower frame. Radiance measured by AVIRIS varies primarily as a function of the solar spectrum, atmospheric scattering at shorter wavelengths and strong atmospheric absorption at specific wavelengths in the near-infrared. The overall shape of both spectra is controlled by the solar spectrum, which peaks at 490 nm and resembles a Planck function. Increasing radiance towards the shortest wavelengths is caused by Rayleigh and aerosol scattering. Strong oxygen absorption at 760 nm and water vapor absorption at 940, 1130, 1350 and 1900 nm are evident. Surface reflectance differences account for lower reflected radiance in the visible and short-wave infrared (1650 nm +) in *Ceanothus* relative to the beach target.

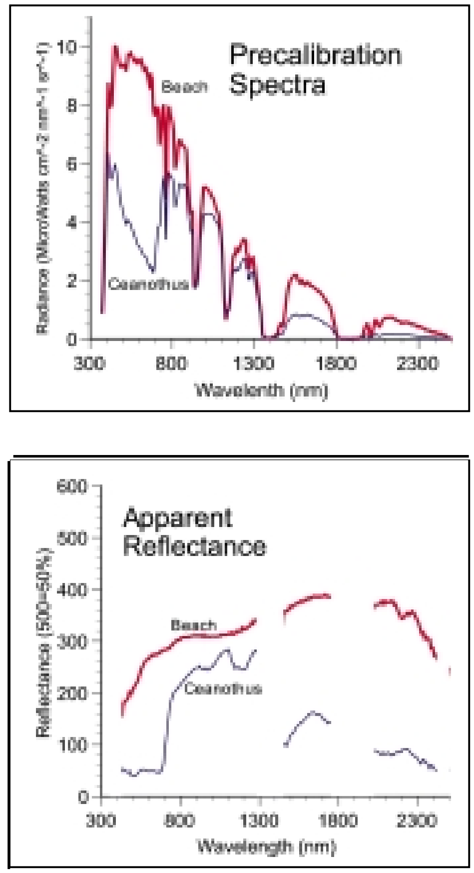


Figure 1. AVIRIS Radiance and reflectance spectra. Radiance spectra, which cannot be directly compared to laboratory or field measured spectra and will vary depending on solar and atmospheric conditions, can be easily interpreted once converted to reflectance.

In order to retrieve surface reflectance, measured radiance is fitted to modeled radiance for a specific geographic location, time and date, while allowing water vapor and liquid water to vary as parameters. Apparent surface reflectance is calculated as measured radiance divided by modeled radiance after removing atmospherically scattered path radiance. Each spectrum is corrected for a unique atmosphere. The resulting apparent reflectance spectra are comparable to spectra acquired by a field or laboratory spectrometer (Figure 1, lower frame).

Apparent surface reflectance makes it possible to relate remotely sensed reflectance directly to identifiable materials. SMA is a technique that models reflected radiance from a heterogenous surface as the sum of the spectra of materials within the field of view (Adams et al., 1993). It is a potentially valuable tool for fire hazard research in that it can describe the areal proportions of live green and non-photosynthesizing canopy components. Once converted to reflectance, it is possible to identify "pure" spectra from a library of laboratory or field spectra and unmix image data as mixtures of these pure spectra, known as reference endmembers. Typical reference endmembers include shade, various soils, non-photosynthetic vegetation (NPV) and green vegetation (GV: Roberts et al. 1993). SMA using reference endmembers has been shown to be an effective tool for identifying surface constituents and monitoring changes due to phenology (Roberts et al., 1997a) and land-cover change (Roberts et al., 1998b). An example, comparing fall and spring models for the SMM is shown to the right (Figure 2). NPV, GV and soil fractions are shown as red, green and blue, respectively. High soil fractions occur in urban areas, along roads and within the fire scar of the Calabasas fire. High GV fractions occur during both seasons in oak woodlands, riparian areas and hard chaparral. Grasslands are characterized as having high NPV fractions in both seasons (red) while soft chaparral retains foliage in the spring but has dropped most leaves by fall and thus has a mixture of NPV and GV.

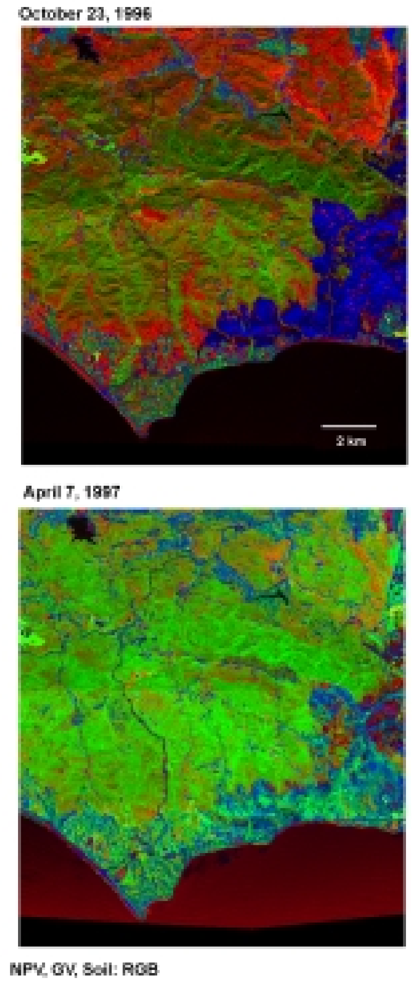


Figure 2. Spectral mixture model of a fall and spring pair of AVIRIS images.

In order to retrieve surface reflectance it is necessary to fit water vapor and liquid water as they vary spatially. The result is a map that shows spatial variation in column water vapor and equivalent liquid water thickness (Figure 3). Water vapor (Left), is largely controlled by fine scale topographic variation and resembles an inverted digital elevation model (Low elevations have a longer path and thus higher water vapor, high elevations have a shorter path and low water vapor). Equivalent liquid water thickness (herein referred to as liquid water) is primarily restricted to water in green leaves (Roberts et al., 1997a; Ustin et al., 1998). Canopy liquid water varies primarily as a function of the water content of leaves within the canopy and the number of leaves light encounters as it scatters through the canopy. As the number of leaves within a canopy increases, the expression of liquid water in spectra typically increases as well. Roberts et al. (1998c) investigated the potential of liquid water as a surrogate measure for measure for LAI and found a linear correlation up to LAI exceeding eight. Furthermore, liquid water was more sensitive to phenology than the NDVI.

Ustin et al., (1998) explored the potential of liquid water as a direct measure of leaf moisture content. While structural parameters, such as LAI, complicate estimates of leaf moisture by creating an ambiguity between water trapped in individual leaves and water expressed by multiple leaves, seasonal changes in the relationship between greenness and liquid water offer the potential of separating these two factors (Figure 4). When comparing fall and spring liquid water to the GV fraction, the slope between normalized GV (y) and liquid water (x) is shallower for spring. This slope change implies a higher liquid water content for a given amount of green leaf material and thus a change in leaf moisture. The intercept during the spring is slightly positive, while the fall is slightly negative. A decrease in the intercept towards fall could be caused by an increase in exposed soil of NPV due to leaf drop or a change in leaf orientation (Hanes, 1988).

Species level maps are important because fire related properties, such leaf surface to volume ratios, green

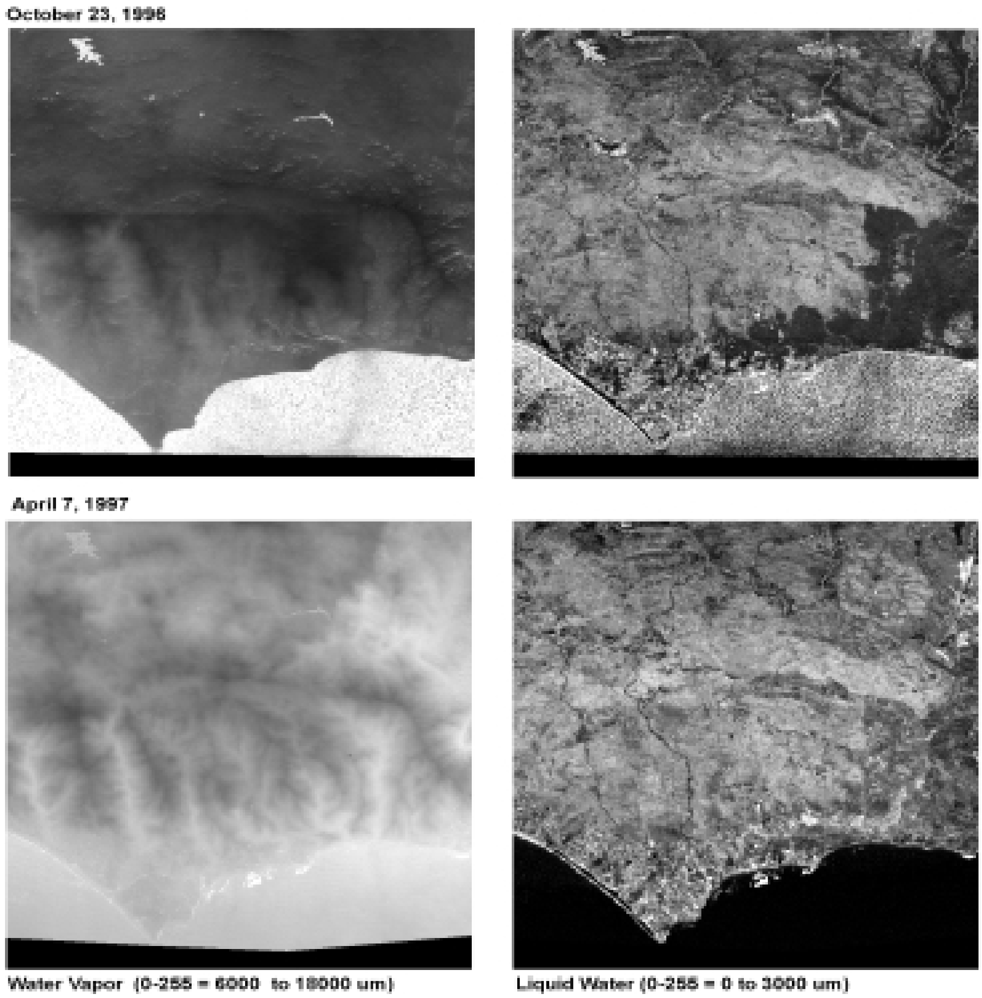
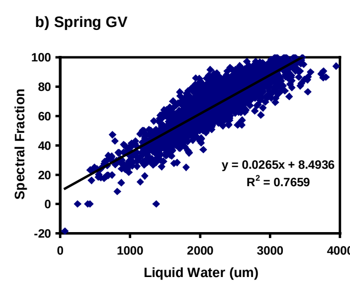


Figure 3. Water vapor and liquid water images for October 23, 1996 and April 7, 1997. Lower humidities in the fall result in lower column water vapor in the October image relative to April. Most natural vegetation shows higher liquid water in the spring. The fire scar of the Calabasas fire is clearly evident as a region of low liquid water in both image dates. Soft chaparral and grasslands show significantly lower liquid water in the fall relative to spring, whereas hard chaparral shows only moderate changes. High water vapor values over water are an artifact due to low reflected radiance over water bodies.

leaf to woody biomass and ignition temperatures vary between species. Canopy reflectance varies between species primarily due to the chemistry/optical properties of canopy components (leaves and branches), their physical arrangement (structure), lighting and viewing geometry. While species are defined based on ge-



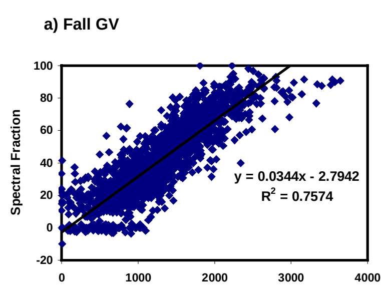


Figure 4. Seasonal changes in liquid water vs GV.

netics and floral taxonomy, chemical and architectural differences between species are commonly sufficient to generate unique spectra. Broad band sensors can map species, but, due to a paucity of bands are typically better suited to mapping broad land-cover categories or vegetation communities. In contrast, an imaging spectrometer is less wavelength limited and has the ability to quantify subtle spectral differences (due to chemistry or structure) that are not captured by broad band systems. Roberts et al., (1997b, 1998d) introduced the concepts of a regionally specific spectral library and Multiple Endmember Spectral Mixture Analysis (MESMA). Using MESMA, the number and types of endmembers selected are allowed to vary on a per- pixel basis, making it possible to map hundreds of unique materials in the landscape. When combined with a regionally specific library, MESMA has been used to map species and unique land-cover types across a diversity of ecosystems including southern California chaparral (Roberts et al., 1998d) alpine areas of the Sierra Nevada (Painter et al., 1997) and the Canadian boreal forest (Roberts et al., 1999a). High resolution AVIRIS has significantly expanded the ability to develop regionally specific libraries and map plant species (Roberts et al., 1999b).

AVIRIS FIRE HAZARD RESEARCH

Study Site

Our primary focus has been in two regions of Southern California, the SMM and Santa Barbara Front Range (Figure 5). These areas have a mediterranean climate characterized by relatively mild winter and summer temperatures, winter precipitation and summer drought. The fire season starts as early as May and progresses through October or November until precipitation is sufficient to raise fuel moisture. Both regions experience extreme fire weather. In the SMM, Santa Ana Winds develop in late spring and early fall and lead to high winds, temperatures that can exceed 45 °C and relative humidities near zero. The Santa Barbara area experiences smaller scale extreme events, called Sundowners that occur when high pressure develops north towards Santa Maria and low pressure builds off of the coast.

These areas are considered ideal for this study because of the diversity of vegetation, complex land-use patterns, high frequency of fires and very real need for improved assessment of fire in the area. Many of the examples discussed in the Background section were derived from research in the SMM.

Data

Supporting data include over 6,000 field spectra acquired between 1995 and 1998, over one hundred AVIRIS scenes acquired between 1994 and 1998, approximately 300 reference vegetation polygons and 17 destructive biomass harvests performed by Jon Regelbrugge. Field spectra were acquired using an Analytical Spectral Devices (ASD) full range spectrometer (Analytical Spectral Devices, Boulder, CO) standardized to a spectralon reflectance panel (Labsphere, Inc., North Sutton, NH). Field spectra were measured 1-5 meters above the canopies of all dominants in the SMM during the spring and the fall. Additional NPV

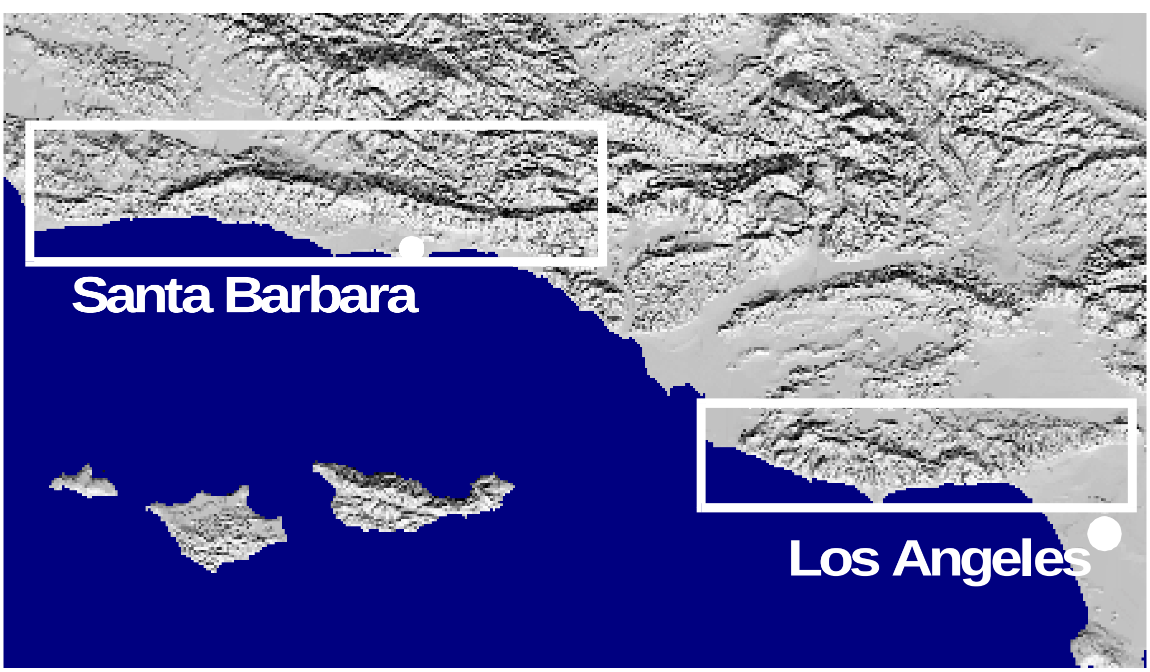


Figure 5. Index map showing study regions.

and leaf level spectra were measured using a Cary-5E (Varian, Inc. Sunnyvale, CA) at UC Davis (Ustin et al., 1998).

AVIRIS data were acquired starting in the fall of 1994. The SMM have been reflown successively to establish longterm patterns of change and provide current fuels maps. Acquisition dates include October 19, 1994, three dates in May 1995 (May 9, 1995 is shown in Figure 4), one flight in fall 1995, two flights in fall 1996 (pre and post Calabasas fire on October 17 and October 23, 1996), a spring/fall pair in 1997 and a spring/fall pair in 1998. Additional high resolution data (4 m) were acquired on October 5, 1998. Example spectra from high resolution AVIRIS are shown in Figure 6. All data from the SMM have been processed to apparent surface reflectance, used to map liquid water

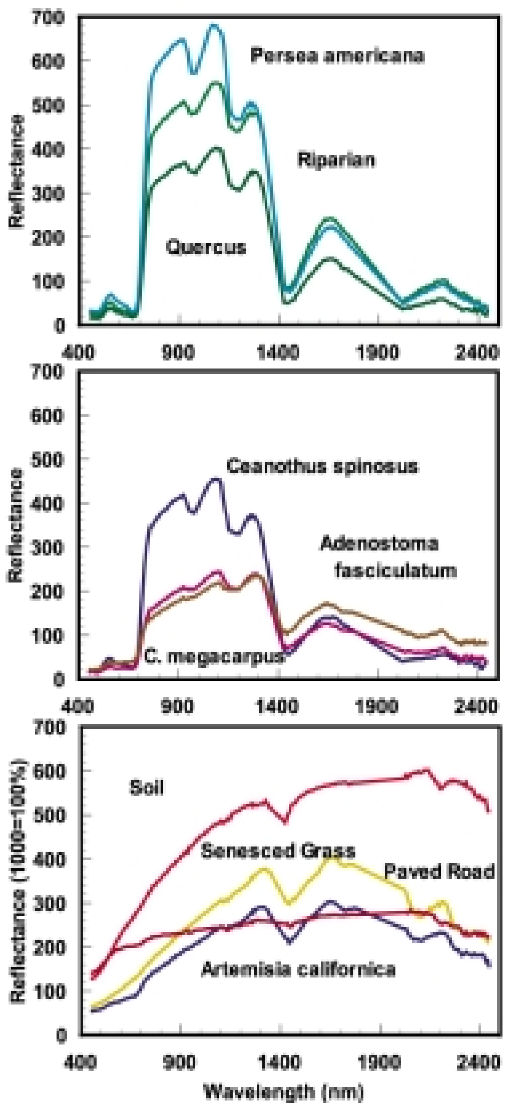


Figure 6. AVIRIS reflectance spectra.

and processed using SMA to map NPV, GV, soil and shade fractions. Species level maps have been generated for all fall data sets using a fall spectral library. All map products have been coregistered to a 10 meter georeferenced SPOT image.

AVIRIS processing was initiated in the spring of 1998 in the Santa Barbara Front Range. Data in this area include a spring/fall pair and two high resolution flight lines. All coarse resolution (20 m) data have been processed to surface reflectance, used to map liquid water and analyzed using SMA and georeferenced. Fall 1998 data have been used to map vegetation species. Additional GIS layers include a detailed fire history, soils maps and high resolution DEM used to generate maps of insolation.

Methods

Apparent surface reflectance, liquid water and water vapor were mapped using the approach described by Green et al., (1993) modified to include ground reflectance target (Gardner, 1997; Roberts et al., 1999a). SMA was implemented for both spring and fall data sets using a reference endmember library of laboratory reflectance spectra of green leaves, NPV and soil collected in the SMM. Reference endmembers were selected to to generate fractions that matched visual estimates of green vegetation, shade and NPV for *Ceanothus* and *Adenostoma* derived from the field as described by Roberts et al. (1998b). Fraction images of GV, NPV, soil and shade were generated by modeling each pixel as a combination of two endmembers (ie, GV and NPV) and shade, then selecting the three endmember model with the smallest Root Mean Squared Error (Ustin et al., 1998).

Species Level Maps

Species level maps were generated using MESMA and a spectral library developed from a combination of field and laboratory spectra and 4 meter spectra derived from high resolution AVIRIS (Roberts et al., 1997b, 1999b). Species level maps for high resolution and 20 m AVIRIS data are shown in Figure 7. Several hard chaparral and soft chaparral species were mapped including two species of *Ceanothus* (*spinosus* and *megacarpus*), A*denostoma fasciculatum* and *Artemisia californica*. Additional regions were mapped as mixed hard or soft chaparral where two or more species were intermixed below a 4 meter resolution. Riparian vegetation and oak woodlands were not mapped to species level due to insufficient knowledge of the distribution of different tree species in these commu-

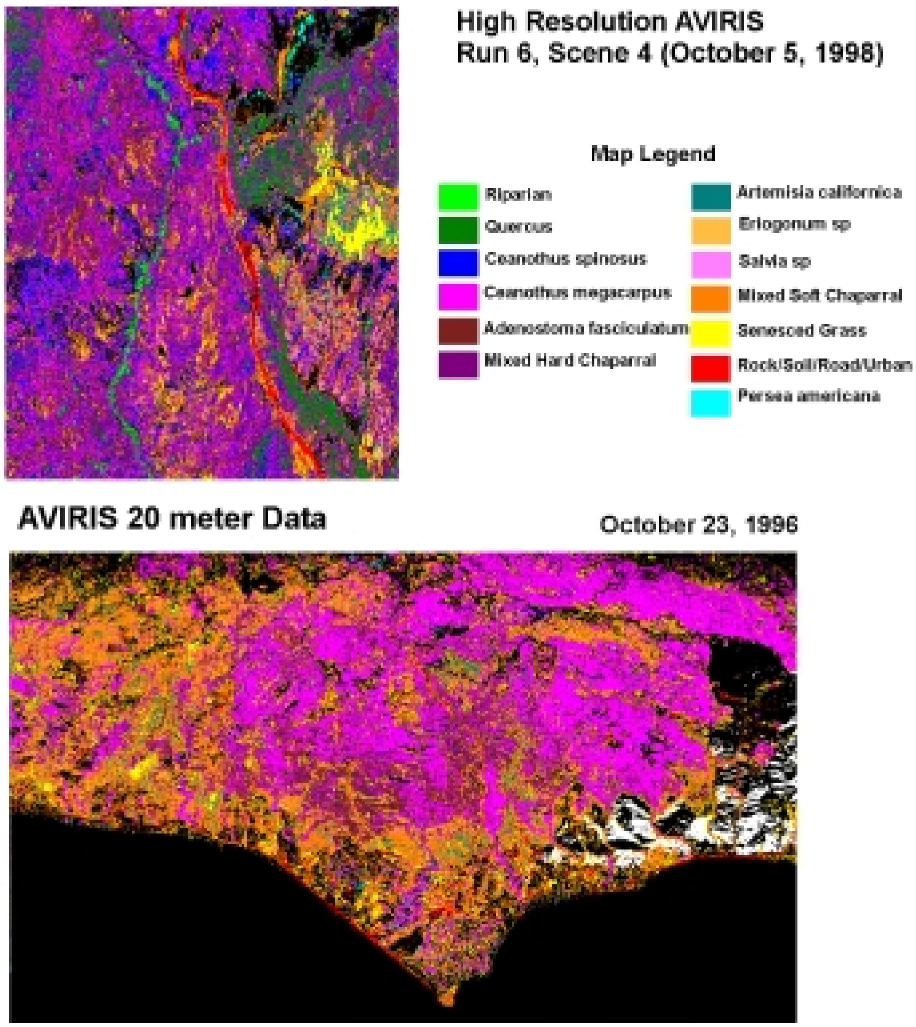


Figure 7. Species maps generated from MESMA.

nities. *Eriogonum* and *Salvia* were mapped to the generic level. *Persea americana* was included as a non-native tree common in parts of the range.

Initial results are promising. At fine resolution, we were able to distinguish two species of *Ceanothus*, a majority of the dominants and riparian areas. Areas mapped as senesced grass, *Eriogonum* (primarily *fasciculatum*), *Adenostoma* and both *Ceanothus* dominants match polygons for these species well. At 20 meter resolution, MESMA correctly maps a majority of the hard chaparral as consisting of either *Ceanothus megacarpus* or *Adenostoma*. However, it undermaps *Ceanothus spinosus* and fails to locate most of the riparian areas, which occur at or below the 20 meter resolution of the sensor. A visual comparison of the 4 meter and 20 meter maps suggests that a greater proportion of the soft chaparral is assigned to a mixed soft chaparral class at 20 meter resolution.

Integration and Fire Spread Modeling

In order to parameterize fire spread models, species level maps were initially cross-walked to the 13 standard Anderson fuel models and four custom models developed by Jon Regelbrugge for A*denostoma*, *Ceanothus* and *Artemisia*. Accuracy assessment was performed on species maps by comparing areal proportions of plants determined from the ground in each field polygon to AVIRIS species maps for fall 1994 and fall 1996.

A long-term objective of this research is to assess wildfire hazard. One of the methods we are employing is to use AVIRIS products to parameterize fire spread simulations. Currently, we are focusing on two models, FARSITE (Finney, 1998) and FIRETEC (Linn, 1997). In order to better incorporate new AVIRIS parameters, we are modifying models to include some variation in live moisture and green live biomass.

To test our ability to predict fire spread from AVIRIS maps we are taking advantage of two fires that have occurred in our study region. The first, the Calabasas fire, burned between October 21 and 27, 1996, 4 days after one AVIRIS acquisition. A second AVIRIS flight was obtained on October 23, 1996, before the fire was fully contained. This fire burned a total of 5250 hectares and occurred during a Santa Ana Wind event. The second case is the Ogilvy fire. The Ogilvy fire burned between October 16 and 24, 1998, in Santa Barbara County north of the city of Santa Barbara. It occurred under relatively mild fire weather, burning a total of 1650 hectares. AVIRIS data were acquired in late September, within several weeks of the fire. We have run preliminary fire spread simulations for both fires using FARSITE and are currently parameterizing FIRETEC for the Calabasas fire in collaboration with Los Alamos National Laboratory.

Maps of GV, NPV and soil are shown prior to and after the Calabasas fire (Figure 8). The most evident feature is the prominent fire scar, which is modeled primarily as bare soil. A comparison between the two images shows that most of the fire was restricted to grasslands or soft chaparral, characterized as having high NPV fraction. The one exception occurred in the vicinity of Malibu bowl, where the fire burned up hill through hard chaparral following a shift in the wind direction.

DISCUSSION

Hyperspectral sensors have the potential for producing a large number of products for fire hazard assessment. Hyperspectral sensors capture many of the elements essential to fuels mapping including accurate vegetation identification (potentially to species levels) and measures of green live biomass and live fuel moisture. When combined with analysis tools such as SMA, hyperspectral data can be used to map areal portions of live and non-photosynthesizing canopy components. Accurate reflectance retrievals are essential for intercomparison of data sets and change detection.

However, the data produced by such systems have severe limitations and are not equally applicable across all fire regimes. In Southern California chaparral, wildfire propagates primarily as crown fires. As a result, the fuel consists primarily of fine green leaves and living and non-living stems and twigs and are directly measured by AVIRIS. In contrast, fire in many forested ecosystems fires are more restricted to ground fires (Pyne et al., 1996). In this case, an airborne or spaceborne system cannot sample the fuels directly.

Accuracy assessment remains a problem. Many of AVIRIS products, such as liquid water, lack sufficient ground testing to determine their validity. Seasonal and spatial patterns are self consistent, but a study that definitively shows how the liquid water signal propa-

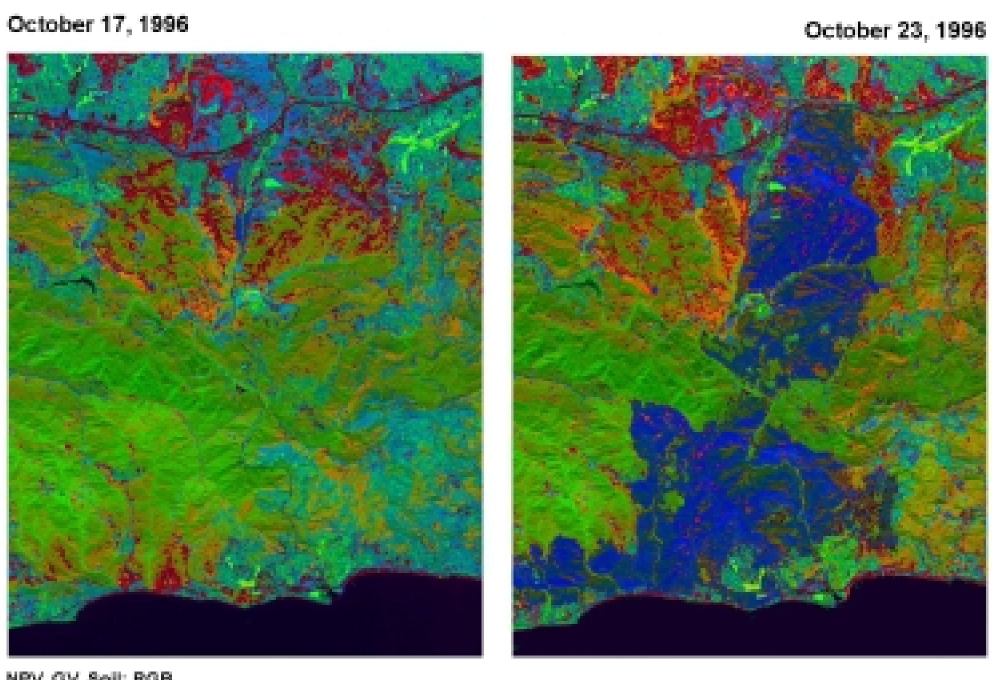


Figure 8. Spectral mixture models before and after the Calabasas fire.

gates as light scatters through a canopy and thus separates the contribution of leaf moisture from green leaf biomass is currently lacking. Determining the accuracy of species level maps has also proven to be challenging. A field polygon reports the areal proportions of species but does not report their spatial distribution within that polygon. In contrast, AVIRIS will assign one to two species to each pixel, thus generating finer scale detail than exists in the reference data. More rigorous use of transects could resolve this spatial mismatch, but at the cost of a prohibitively expensive field campaign. Species-level maps for the SMM have been tested for accuracy using fuzzy accuracy assessment and shown good agreement at least to the generic level (Gardner, 1997). However, in this case the number of field polygons were insufficient. Furthermore, later analysis showed significant mismatches between AVIRIS maps and field polygons, many of which were either due to land-cover changes or errors in the reference data. Even more traditional methods such as SMA lack adequate testing. Whereas fraction estimates from SMA have been validated in desert and semi-desert communities (ie, Smith et al, 1990), a rigorous test of SMA in chaparral is lacking. The dynamic nature of the landscape, and the fact that most of the data are historical further complicate efforts to test SMA.

Integration of remote sensing products and fire spread models remains challenging. Few fire spread simulations are designed to accommodate the products we can produce. Model parameters typically include characteristic surface to volume ratios, packing ratios, fuel loadings for different fuel size classes, height to crown, dead fuel moisture etc (Pyne et al., 1996). Few of these are parameters we directly measure. Parameters such as GV and NPV fractions do not fit readily into any existing fire spread model, although they effectively capture the areal proportions of relevant fuels and their seasonal changes. Either new fire spread models need to be developed, or creative ways need to be employed to better utilize remotely sensed products.

Finally, the issue of scale remains a challenge for all hyperspectral systems. Currently no spaceborne system exists. As a result, hyperspectral data are restricted geographically to a relatively small number of regions. Although a number of spaceborne systems are likely to launch over the next few years, these systems will still have limited scaling capabilities due to large data volumes and relatively few data takes. Hyperspectral data are further limited temporally, consisting primarily of a single overpass or annual repeat passes. In a few cases, such as ours, two or more seasonal flights are acquired in a year, typically one in late spring and another in early fall. Given such limited temporal sampling, a system such as AVIRIS is not capable of monitoring fuel properties as they evolve through a fire season. In order to incorporate greater temporal sampling we are currently incorporating SeaWiFS into our analysis. SeaWiFS is an eight channel, well calibrated system that acquires global, daily coverage at a nominal resolution of 1 km. We plan on integrating AVIRIS reflectance and SeaWiFS to develop spectral mixture models that can be applied to SeaWiFS to track seasonal changes in GV, NPV, soil and shade at high temporal frequency.

STRATEGIES FOR HYPERSPECTRAL SYSTEMS

The optimal strategy for using hyperspectral data is to integrate these data into studies that use more conventional remote sensing data. Hyperspectral systems have the potential for adding value to data acquired from any broad band sensor that measures the visible and near-infrared. High quality apparent reflectance from a system such as AVIRIS can be used to improve the calibration of a wide array of other sensors. Species-level maps can be used to validate maps generated from other sensor systems. Products such as liquid water can be combined with techniques such as SMA to develop alternate tools for assessing canopy structure and moisture in the absence of direct measures of liquid water from spectra.

In order to best utilize hyperspectral data we would propose an integrated strategy that utilizes hyperspectral data to provide accurate maps of fuels at fine spatial resolutions in most ecosystems. These maps would be used to guide a more regional analysis using sensors such as Landsat 7 Enhanced Thematic Mapper (ETM) to map large areas of the United States. Fine temporal measures of the changing state of fuels could be acquired at 1 km resolution using SMA applied to data such as SeaWifs or MODIS. Thousands of AVIRIS scenes have been acquired within the United States over the past decade, sampling most of the major ecosystems in North America. SeaWifs has been operational since the fall of 1997 and Landsat ETM successfully launched in April, 1999. The data exist to develop such a strategy.

ACKNOWLEDGMENTS

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